*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-2.043 (2007)*

Microtearing instabilities and electron transport in the NSTX spherical tokamak

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Introduction

The source of electron transport in magnetized plasmas, which can be a major obstacle in the way toward practical nuclear fusion power, is still an unsolved problem in magnetic fusion research. The observed electron energy transport is much larger than one would expect from diffusive process due to Coulomb collisions. Because of the success of ion temperature gradient mode (ITG) turbulence in explaining anomalous ion transport at conventional aspect ratio, it is natural to think that electron temperature gradient mode (ETG) turbulence may be responsible for electron transport. While active theoretical and experimental research is being carried out along this path, a mechanism based on broken magnetic surfaces[1] is a viable explanation in some situations. Imperfect magnetic surfaces can be produced by the microtearing instability driven by electron temperature gradient.[2] These modes are stable in conventional tokamaks[2] except near the plasma edge where electron temperature is low, but they can be the most unstable mode in a spherical tokamak like NSTX[3] and MAST[4] over a certain range of parameters. Since the magnetic field in a spherical tokamak is substantially lower than that in a conventional tokamak, nonlinear theory[5] predicts that the microtearing modes should saturate at a significantly higher amplitude, making it the dominant mechanism that governs electron transport in some spherical tokamak plasmas. This is consistent with the high electron thermal conductivity in the plasma core and its recently observed strong magnetic field dependence.[6]

Experimental Results

The experiment was carried out in NSTX operating with major radius $R=0.85m$, and minor radius $a=0.67m$, in H-mode discharge with $6\ MW$ deuterium neutral beam heating at $I_p=0.75\ MA$, $B_t=0.5\ Tesla$. At $t=0.9\ s$, Motional Stark Effect measurements of the magnetic field pitch indicate that the plasma had a monotonically increasing q with $q(0)>1$ so that there are no sawteeth or other significant MHD activity in the plasma core observable by either the soft X-ray array or Mirnov coils. There is a steep temperature gradient at $X=(\phi/\phi_a)^{1/2}\geq 0.4$ where ϕ represents the toroidal flux. The GS2 gyrokinetic stability code is used to calculate the linear growth rate and the eigenmode structure for the most unstable mode in a preset range of wave numbers. The linear growth rates were calculated for wavenumbers in the range $k\rho_s = 0.1$ *to* 1.0, and microtearing modes were found to be the most unstable mode in the region X=*0.4 to 0.75* of this plasma. Fig.1 shows the linear growth rate of these unstable modes for various wave numbers at $X = 0.4, 0.5, 0.65$ and 0.75. Since microtearing modes have $k_{||}$

$= 0$ and an even parity δB_r, these modes are very effective in producing magnetic islands near rational magnetic surfaces where $q = m/n$. When the islands are small, stochastic field lines are localized in the vicinity of the separatrix. Island chains of different helicity are separated by good magnetic surfaces (KAM surfaces), which serve as electron transport barriers. Substantial heat transport should ensue when either adjacent island chains or resistive layers overlap.[7] The latter requires[7] the poloidal mode number $m > m_o = q(2q'\rho_s)^{-1/2}$ where $\rho_s = (2T_e/m_i)^{1/2}/\omega_{ci}$ and q' denotes the derivative of q with respect to the minor radius r. Most of the unstable modes shown in Fig.1 satisfy the resistive layer overlap criterion. One can also estimate the saturated island width based on the mode amplitude $\delta B/B \approx \rho_e/L_T$ and find that adjacent island chains also overlap. Therefore, the region $0.4 \le X \le 0.75$ should be occupied by stochastic magnetic field lines.

Data Interpretation

The electron thermal diffusivity χ_e in a stochastic magnetic field can be derived using a test particle transport model;[1] χ_e is proportional to the magnetic field diffusivity $D_M = R|\delta B/B|^2$. Following Kadomtsev,[8] the connection length qR is chosen to be the magnetic field correlation length L_c. Then, the thermal electrons with thermal velocity v_e in this NSTX discharge are in the collisional regime, i.e., the electron mean free path λ_{mfp} is shorter than L_c, and χ_e due to saturated microtearing modes becomes

$$\chi_e = (\rho_e/L_T)^2 R\, v_e\, (\lambda_{mfp}/L_c) = (\rho_e/L_T)^2\, v_e^2/(\nu_{ei} q) \quad , \qquad (1)$$

where ν_{ei} is the electron-ion Coulomb collision rate. All the values of the plasma parameters on the right hand side of Eq.(1) can be obtained from the plasma equilibrium. These theoretical values are compared to the χ_e obtained from transport analysis with the TRANSP code. The theoretical values are roughly a factor of 2 lower as depicted in Fig.2. It should be noted here that Drake's nonlinear theory[5] was derived with the assumption that the plasma electron density is uniform, and the instability is entirely driven by the electron temperature gradient. This is not exactly the case in our experiment where we have $2 > L_n/L_T > 1$. The density gradient effect can be approximately accounted for by replacing L_T in Eq.(1) with L, where

$$L^{-1} = L_T^{-1} + L_n^{-1} . \qquad (2)$$

After such a substitution, the theoretical χ_e in the region $0.4 \le X \le 0.75$ is found to be within 40% of the experimental value, which is well within the uncertainty of the transport analysis and the nonlinear theory. This good agreement should not be a surprise because all the assumptions used in the test particle transport theory are valid in the experiment. $T_e(r)$ is very flat near the magnetic axis ($X \le 0.3$) where microtearing modes are stable; χ_e there is very large due to other mechanisms not yet identified.

Should microtearing modes be the dominant electron transport mechanism, χ_e will be significantly reduced when these modes are stable, which is the case in plasmas with reversed central magnetic shear. The growth rate at $X = 0.3$ was calculated for such a shot (#116960) and its comparison shot (#115821). Microtearing modes are unstable in #115821 over a wide range of $k_\theta\rho_s$ and satisfy the overlap criterion, but not in #116960 where the magnetic shear is reversed. Both shots have the same plasma current, density, magnetic field, plasma shape, position and neutral beam heating power, but the central electron temperature is substantially higher (*2 keV vs 1.4 keV*) in #116960 where microtearing modes are stable. This is a strong indication that microtearing modes may be the dominant mechanism responsible for the electron transport at this location in this type of plasma. This instability could be the most likely limit on electron temperature in STs where the intrinsic high ExB shears can stabilize the usual long wavelength instabilities.[9] At present, however, there is no diagnostic on NSTX capable of measuring the internal magnetic field fluctuations to confirm the existence of microtearing modes.

Summary

In summary, we have shown that the observed electron thermal conductivity in one type of NSTX discharge can be explained by the magnetic fluctuations from microtearing instabilities. These modes saturate at large amplitude due to the low magnetic field; they produce global stochastic magnetic fields, and therefore Eq.(1) is applicable. This explains the good agreement between the theoretical and the observed electron thermal conductivity over the entire region where the microtearing mode is the fastest growing instability with $0.3 \le k_\theta\rho_i \le 1$. NSTX has the flexibility to operate in many regimes. This instability could be suppressed by reversed magnetic shear, by raising the electron temperature such that $\nu_e < \omega_{*e}$, or by operating at higher magnetic field to reduce the saturation amplitude. This result does not rule out ETG turbulence in controlling electron transport in NSTX. ETG modes are calculated to be important in other discharges and/or at other locations.

Acknowledgements: We are greatly indebted to Drs. M. G. Bell, A. L. Roquemore and the NSTX technical staff whose hard work made this experiment possible. This work is supported by the DoE contract No. DE-AC02-76CH03073.

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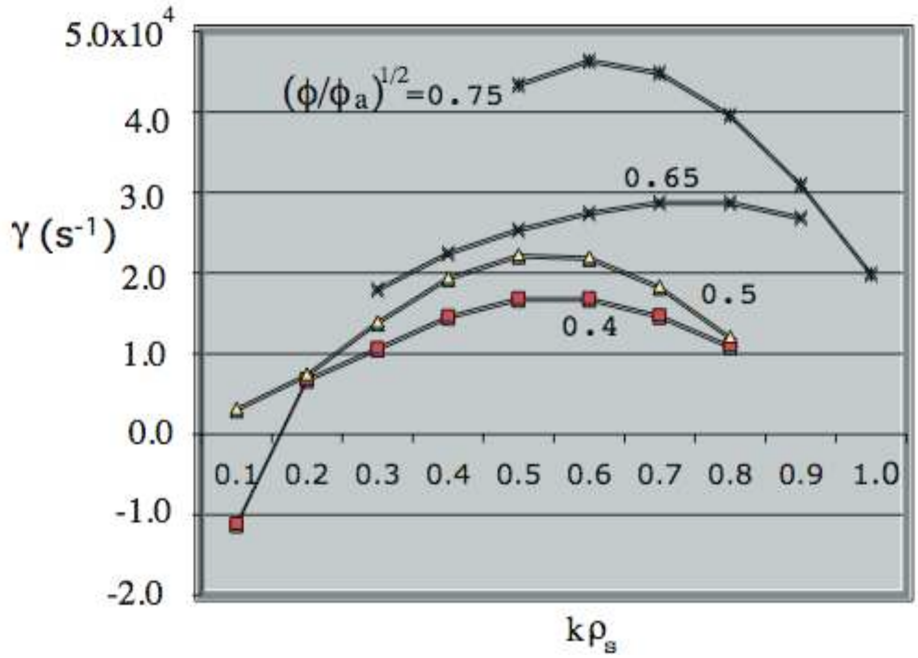

Fig.1 Linear growth rate of unstable microtearing modes at various radial location.

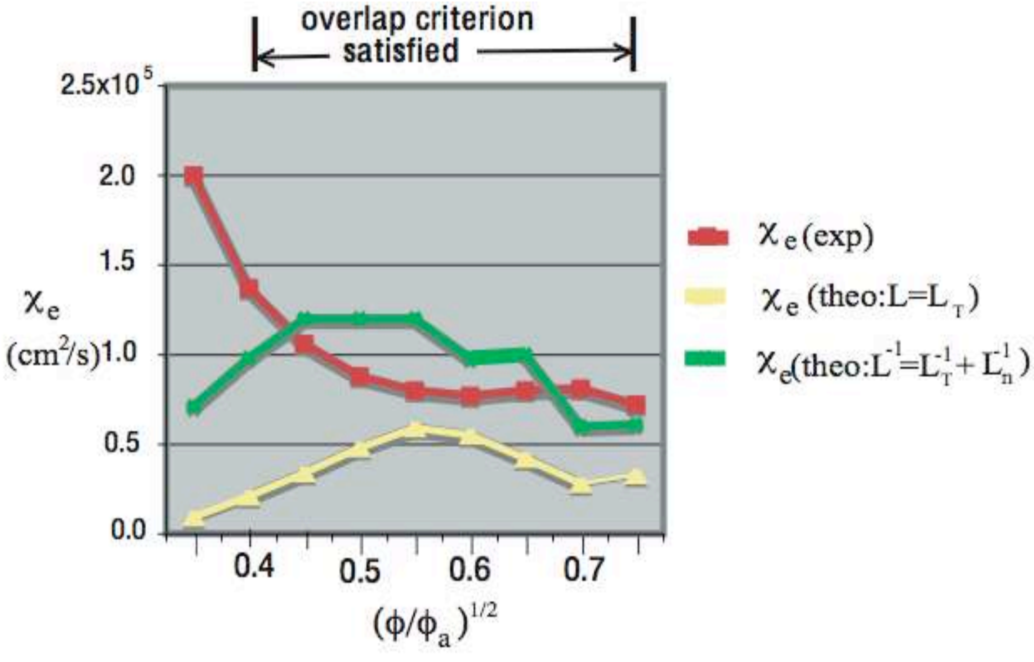

Fig.2 Comparison between values of electron thermal conductivity from TRANSP analysis of experimental data and those calculated from Eq.(1).